REVIEW OF THE COLUMBIA/SNAKE RIVER TEMPERATURE TMDL FOR THE COLVILLE AND SPOKANE TRIBES

Prepared for

U.S. Environmental Protection Agency
Region 10
Seattle, Washington

Prepared by

George Bowie / Clayton Creager
Tetra Tech, Inc.
3746 Mt. Diablo Blvd., Suite 300
Lafayette, CA 94549
(925) 283-3771

September 14, 2002

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Review of the Columbia/Snake River Temperature TMDL for the Colville and Spokane Tribes

Introduction

A meeting was held on August 6, 2002 in Spokane, Washington between EPA Region X and representatives from the Colville, Spokane, and Kalispel Tribes concerning the Columbia/Snake River Preliminary Draft Temperature TMDL (EPA, 2002). Also in attendance were representatives from Washington State Department of Ecology (WA DOE), Columbia River Inter-Tribal Fish Commission (CRITFC), and Tetra Tech. The purpose of the meeting was to review tribal concerns regarding the effects of implementing the temperature TMDL on tribal resources, and to assess whether the TMDL model would be adequate to address these issues. Technical assistance was requested from Tetra Tech to provide an independent review of the TMDL modeling and to address the tribal concerns. A list of issues and questions were summarized from the meeting and formed the basis for the review.

A follow-up meeting was held in Spokane on September 6, 2002 to discuss the results of the review. In addition to the Colville and Spokane Tribes, representatives from the Nez Perce Tribe also attended the meeting. This report summarizes the meeting discussions and provides recommendations for future studies that could be done to address tribal concerns over the TMDL implementation. Table 1 lists the attendees at the two meetings, and Table 2 lists the major issues that were discussed.

Description of TMDL Model

The Columbia/Snake Rivers Temperature TMDL used EPA's RBM 10 model for the analyses. RBM 10 stands for **R**iver **B**asin **M**odel for EPA Region **10**. RBM 10 is a one-dimensional model that predicts the cross-sectional average temperature at different locations along the length of the Columbia and Snake Rivers. Because it is a one-dimensional model, it only deals with temperature changes along the lengths of the rivers.

Table 1
Attendees at August 6 and September 6 Meetings

Name	Affiliation	Aug 6 Meeting	Sep 6 Meeting
Mary Lou Soscia	EPA	■	■
Rick Parkin	EPA	■	■
Helen Rueda	EPA	■	
Nancy Lui	EPA		■
Gary Passmore	Colville Tribes	■	■
Sheri Sears	Colville Tribes	■	■
Patti Stone	Colville Tribes	■	■
Brian Crossley	Spokane Tribe	■	■
Tom Lorz	CRITFC	■	
John Gross	Kalispel Tribe	■	
Jamie Davis	Nez Perce Tribe		■
Greg Haller	Nez Perce Tribe		■
Ann Butler	WA DOE	■	
Mike Herold	WA DOE	■	
Paul Pickett	WA DOE		■
Clayton Creager	Tetra Tech	■	■
George Bowie	Tetra Tech		■

It does not address issues such as vertical stratification of reservoirs, or differences between the heating of the main river channel and shallow stagnant areas near the river banks. Two- or three-dimensional models would be used for these purposes.

The temperature calculations in RBM 10 are based on well-known thermal energy budget relationships that were established by research at the Tennessee Valley Authority (TVA) during the late 1960's (Wunderlich and Gras, 1967), and which still form the basis of temperature calculations in most water quality models today. The heat exchange across the water surface includes the following processes:

- Shortwave solar radiation
- Reflected shortwave solar radiation
- Longwave atmospheric radiation
- Reflected atmospheric radiation
- Evaporative heat loss
- Heat conduction between the water and air
- Black body back radiation from the water surface

A few models designed for smaller streams in mountainous areas also include additional calculations to account for the effects of topographic or riparian shading on solar heating. However, these effects are not important for the Columbia River due to its large width and relatively unshaded exposure. Heat loads from tributaries, point sources, and nonpoint sources are added to the appropriate reaches of the model based on their temperatures and flow rates.

Table 2
List of Issues Discussed at the August 6 and September 6 Meetings

RBM 10 description

- ✓ Explain the model
- ✓ Review its application for the TMDL
- ✓ Evaluate its appropriateness

Colville temperature criteria are lower than the state criteria. How was this treated in the TMDL?

How were natural temperatures estimated?

Tribal allocations of heat

- ✓ What are the Tribal heat allocations?
- ✓ What will be the impacts of the allocations on the reservation waters?
- ✓ What are the future growth allocations?

Are the existing temperature monitoring stations adequate?

What were the assumptions for the Columbia River inflows from Canada?

What is the perspective on the application of the temperature TMDL to the Pend Oreille River?

TMDL Implementation Plans

- ✓ What form will the implementation take?
- ✓ How long will it take?
- ✓ What is currently known about the implementation plans?

Future studies for assessing potential implementation effects in Lake Roosevelt and other reservoirs (Is RBM 10 adequate, and if not, what other models should be used?)

- ✓ Stratification effects
- ✓ Adequacy of cooling water supply
- ✓ Lake water level changes
- ✓ Changes in flows, currents, residence times
- ✓ Fish habitat degradation (temperature)
- ✓ Fish entrainment
- ✓ Fish migration
- ✓ Cultural resources (lower water levels)
- ✓ Toxic sediments (lower water levels)
- ✓ Landslides (rapid drawdown)
- ✓ Macrophytes (changing water levels)

Meteorological data are required for the heat budget calculations, including the following parameters: solar radiation, cloud cover, air temperature, wind speed, relative humidity, and atmospheric pressure. Data for each portion of the river were taken from the nearest representative weather station, or from several stations when the nearest station did not measure all of the necessary information.

In RBM 10, the heat budget calculations are incorporated into a one-dimensional transport equation that simulates the advective and dispersive transport of heat as water flows through the river basin. The equations are solved using a hybrid Eulerian-Lagrangian method. This approach takes advantage of particular features of each method. The Eulerian reference frame uses a fixed spatial grid, which is convenient for referencing river location and monitoring stations and for incorporating spatial complexity. The Lagrangian reference frame moves with the flow of the water. This reference frame is used for the advective transport processes, since it reduces numerical dispersion and increases the accuracy of the results. The combined method is accurate and efficient, and has been used previously in other models.

RBM 10 is a heat budget and transport model. It requires information from a separate hydrodynamic model to provide the flow, velocity, and channel cross-section information at different locations along the rivers. This information was obtained from two different models, one for each of the two major scenarios analyzed. The Army Corps of Engineers' HEC-5Q model was run for the current impounded condition, and the Army Corps of Engineers' HEC-RAS model was run to estimate natural conditions with the impoundments removed. Both models assumed gradually varied steady flow.

Several different flow values were run to represent seasonal flow differences in the two rivers. These results were used to establish empirical relationships between flow rates and the corresponding water depths, channel widths, channel cross-sectional areas, and velocities at each location in the rivers. The Leopold and Maddock (1953) relationships were used, which expresses each variable (depth, width, cross-sectional area, velocity) as the flow rate raised to some power (exponent) and multiplied by a coefficient. The coefficients and exponents were determined from regression analysis with the hydrodynamic model results. This information was given as input to RBM 10. RBM 10 was then run with daily flow information from USGS gauging stations at various locations along the rivers to drive the transport calculations. The use of the Leopold and Maddock (1953) relationships is a standard procedure used by many river models.

RBM 10 simulations for impounded conditions assume constant geometry and simple continuity (with an assumed constant water elevation) rather than Leopold and Maddock relationships.

EPA checked the accuracy of the hydrodynamic portion of the calculations by comparing the model results with field data and performing flow balances to check continuity. The flow balances were found to be accurate to within 5 to 10 percent (Yearsley, 2002, personal communication).

Some temperature models incorporate the hydrodynamic model directly into the same model. This is particularly important for two- or three-dimensional models that simulate vertical stratification, since temperature (and the corresponding density differences) plays a major role in the hydrodynamics. However, for a one-dimensional river model, temperature does not influence hydrodynamics, so hydrodynamics can be modeled separately.

APPLICATION OF RBM 10 FOR THE TMDL

RBM 10 was set up for the Columbia River extending from the Canadian border to the Pacific Ocean, and for the Snake River from its confluence with the Salmon River to its confluence with the Columbia River. Figure 1 shows the study area. The approximately 950 miles of rivers were divided into a series of 21 reaches, with reach boundaries established at each of the 15 dams, at 5 locations on the lower Columbia River between Bonneville Dam and the Pacific coast, and below Lewiston, Idaho on the Snake River. The reach boundaries on the lower Columbia River were below major cities or point source discharges, at the downstream end of all the point sources, and at the downstream boundary of the riverine portion of the Columbia River. River mile 4 was selected as a reach boundary since the Columbia River behaves more like an estuary than a river below this location. The TMDL analyses were performed at the downstream end of each reach. Table 3 lists the locations of the reaches. At the dams, the model temperatures represent the fore bay temperatures. Each of the 21 reaches was further subdivided into a series of smaller computational elements for the calculations, with length scales on the order of 1 to 10 miles (Yearsley, 2001).

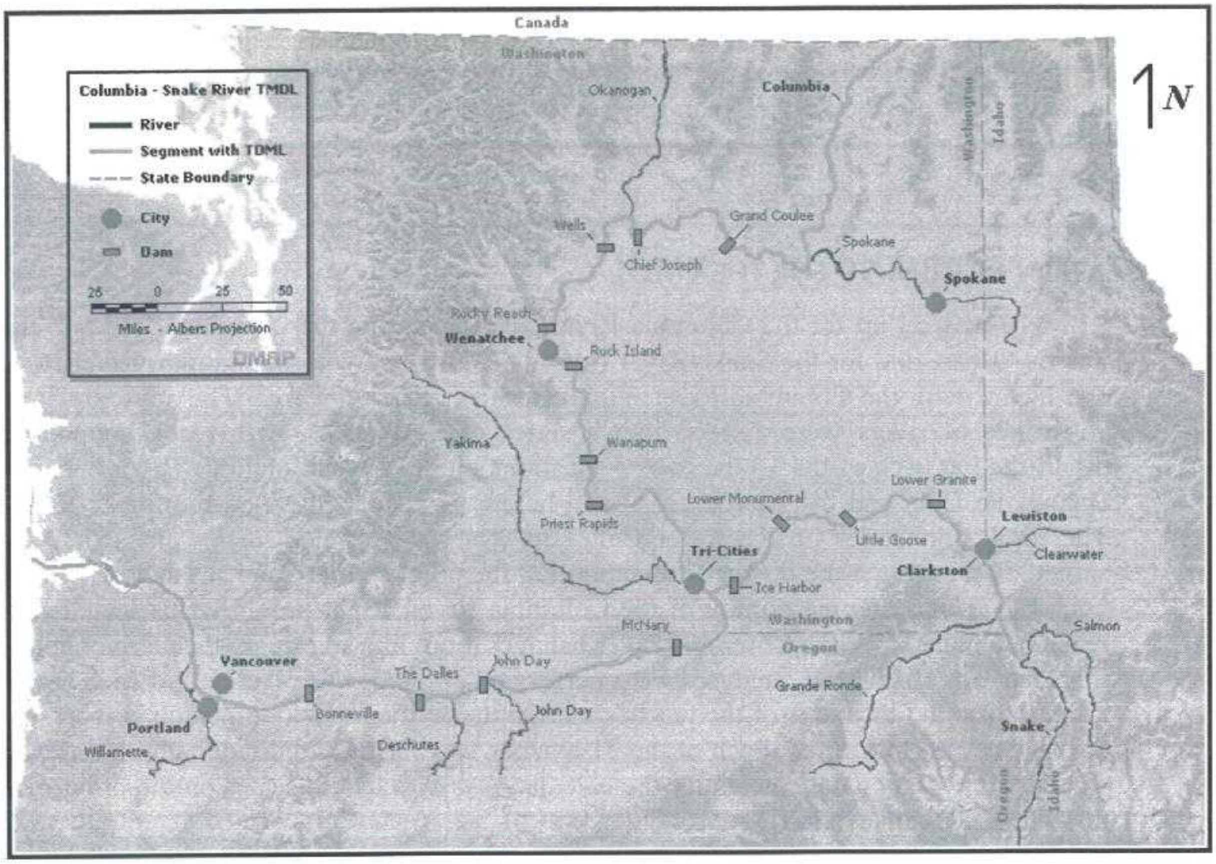

Figure 1. Reaches of the Columbia and Snake Rivers covered by the TMDL (EPA, 2002).

Table 3
TMDL Target Sites Representing Reach Boundaries in RBM 10 (EPA, 2002).

TMDL Reach	Target Site	River Mile
Columbia River		
Canadian Border to Grand Coulee Dam	Grand Coulee Dam	Columbia - 596.6
Grand Coulee Dam to Chief Joseph Dam	Chief Joseph Dam	Columbia - 545.1
Chief Joseph Dam to Wells Dam	Wells Dam	Columbia - 515.8
Wells Dam To Rocky Reach Dam	Rocky Reach Dam	Columbia - 473.7
Rocky Reach Dam to Rock Island Dam	Rock Island Dam	Columbia - 453.4
Rock Island Dam to Wanapum Dam	Wanapum Dam	Columbia - 415.4
Wanapum Dam to Priest Rapids Dam	Priest Rapids Dam	Columbia - 397.1
Priest Rapids Dam to McNary Dam	McNary Dam	Columbia - 292.0
McNary Dam to John Day Dam	John Day Dam	Columbia - 215.6
John Day Dam to The Dalles Dam	The Dalles Dam	Columbia - 191.5
The Dalles Dam to Bonneville Dam	Bonneville Dam	Columbia - 146.1
Bonneville Dam to River Mile 112	River Mile 112	Columbia - 112
River Mile 112 to River Mile 95	River Mile 95	Columbia - 95
River Mile 95 to River Mile 63	River Mile 63	Columbia - 63
River Mile 63 to River Mile 42	River Mile 42	Columbia - 42
River Mile 42 to River Mile 4	River Mile 4	Columbia - 4
Snake River		
Salmon River to RM 138	River Mile 138	Snake - 138
River Mile 138 to Lower Granite Dam	Lower Granite Dam	Snake - 107.5
Lower Granite Dam to Little Goose Dam	Little Goose Dam	Snake - 70.3
Little Goose Dam to Lower Monumental Dam	Lower Monumental Dam	Snake - 41.6
Lower Monumental Dam to Ice Harbor Dam	Ice harbor Dam	Snake - 9.7

RBM 10 was run with 30 years of meteorological data covering the period 1970 to 1999. The daily average temperatures at each site were averaged over the 30 years to estimate a long-term average temperature for each day of the year at each location along the river. By running the model for the existing impounded situation and comparing the results with the estimated natural scenario with the dams and human heat sources removed, it is possible to estimate the temperature changes that have occurred as a result of impoundment and human development in the Columbia/Snake River basins. This was the strategy adopted for the development of the TMDLs.

APPROPRIATENESS OF RBM 10

Temperature models can be distinguished by the number of spatial dimensions (one-, two-, or three-dimensional), the numerical methods for solving the transport equations, and the type of hydrodynamic model used to calculate flows through the water body. The heat budget formulations are generally similar in most models. As the spatial complexity increases, so do the application costs and data requirements. One-dimensional models are generally appropriate for large-scale regional analyses of river basins. Two- or three-dimensional models are more appropriate for individual large water bodies where both vertical stratification and horizontal differences in temperature and circulation are important. They are generally used to evaluate more local issues, and are run for smaller time frames than the 30-year period used for the TMDL. Two- and three-dimensional models generally incorporate hydrodynamics as part of the framework since density differences associated with temperature have a major influence on the hydrodynamics. In contrast, one-dimensional river models can use separate hydrodynamic models to provide the flow information.

A one-dimensional model is appropriate for the purposes of the TMDL analyses because of the large regional scale involved and since in most areas of the rivers, the difference between the surface and bottom temperatures is fairly small. There is generally less than 1 deg. C variation over the cross section of the rivers except near the forebays of some of the deeper dams (McKenzie and Laenan, 1998; Yearsley, 2001). The high flow rates and short residence times through the run-of-the-river reservoirs prevent significant vertical stratification from developing in most locations. However, some stratification occurs near the dams. The maximum temperature difference between surface and bottom is about 8 to10 deg. C in Lake Roosevelt at Grand Coulee Dam at certain times of the year. Much lower temperature differences are found in most of the other reservoirs. Many of the dams on the Columbia River below Grand Coulee have temperature differences of only about 1 deg. C.

The TMDLs were established by removing the dams from the model and estimating what the temperatures would be in the rivers without the dams. For this type of situation, it is reasonable to assume the water column would be fairly well mixed, so the one-dimensional model is appropriate for estimating natural historical temperatures. The TMDL analyses also focused on the cross-sectional average temperatures, so the one-dimensional model was appropriate for that purpose as well.

A one-dimensional model is also consistent with the available monitoring data throughout the system. Long-term monitoring records at most of the dams are available only at a single depth. The calibrated model gives very good results when compared with the field monitoring data. Both the magnitude and timing of human effects are well represented in the model. Figure 2 shows a comparison of the model results and field data at the Bonneville Dam on the lower Columbia River, and Figure 3 shows a similar comparison for the Ice Harbor Dam on the lower Snake River.

One-dimensional models have been used previously for several important studies on the Columbia and Snake Rivers. These include:

- Federal Water Pollution Control Administration (Yearsley, 1969) developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study
- Bonneville Power Administration et al. (1994) used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the System Operation Review
- Normandeau Associates (1999) used WQRRS, a one-dimensional water quality model, to assess water quality conditions in the Lower Snake River for the U.S. Army Corps of Engineers
- RBM 10 was used by the Corps of Engineers for the temperature assessment in the "Lower Snake River Juvenile Salmon Migration Feasibility Report and Environmental Impact Statement" (U.S. Army Corps of Engineers, 2002).

Colville Temperature Standards are Lower than the State Standards

The TMDL analyses considered both the tribal and state standards at each location in the river. Table 4 compares the applicable standards for maximum temperatures. The most stringent of these standards were selected for each reach. The Colville standards were more stringent than the state standards on the Columbia River reach between Grand Coulee Dam and Chief Joseph Dam, so they were used for that reach. The Colville maximum temperature standards are the same as the Washington state standards above and below this reach.

Both the states and tribes have provisions in their standards for situations where the natural temperatures exceed these limits. In these situations, the temperature increases from human activities are only allowed to increase by a small amount over the natural temperatures. This increment is 0.3 deg. C for the Washington and Colville standards, and 0.14 deg. C for Oregon.

Provisions are also included in several of the standards that limit temperature increases from individual point sources and nonpoint sources.

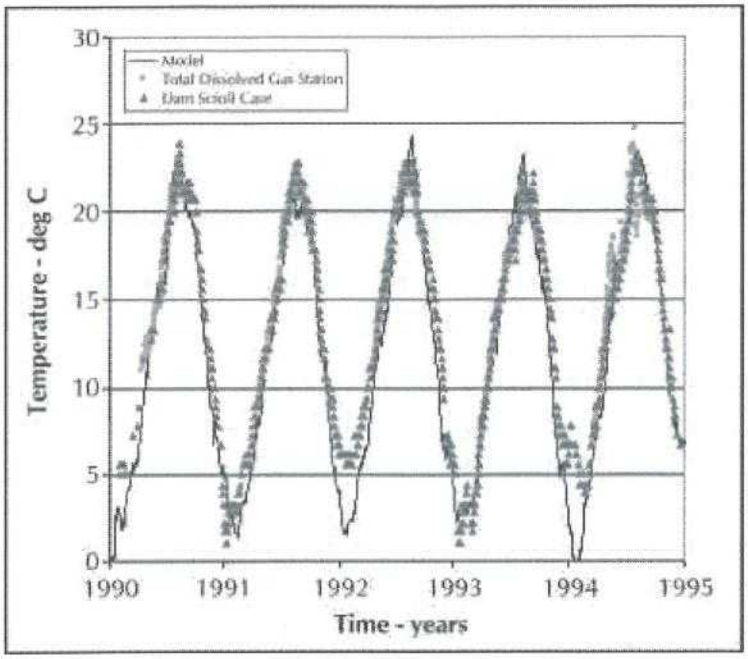

Figure 2. Comparison of predicted and observed water temperatures at Bonneville Dam on the Columbia River for the period 1990-1994 (EPA, 2001).

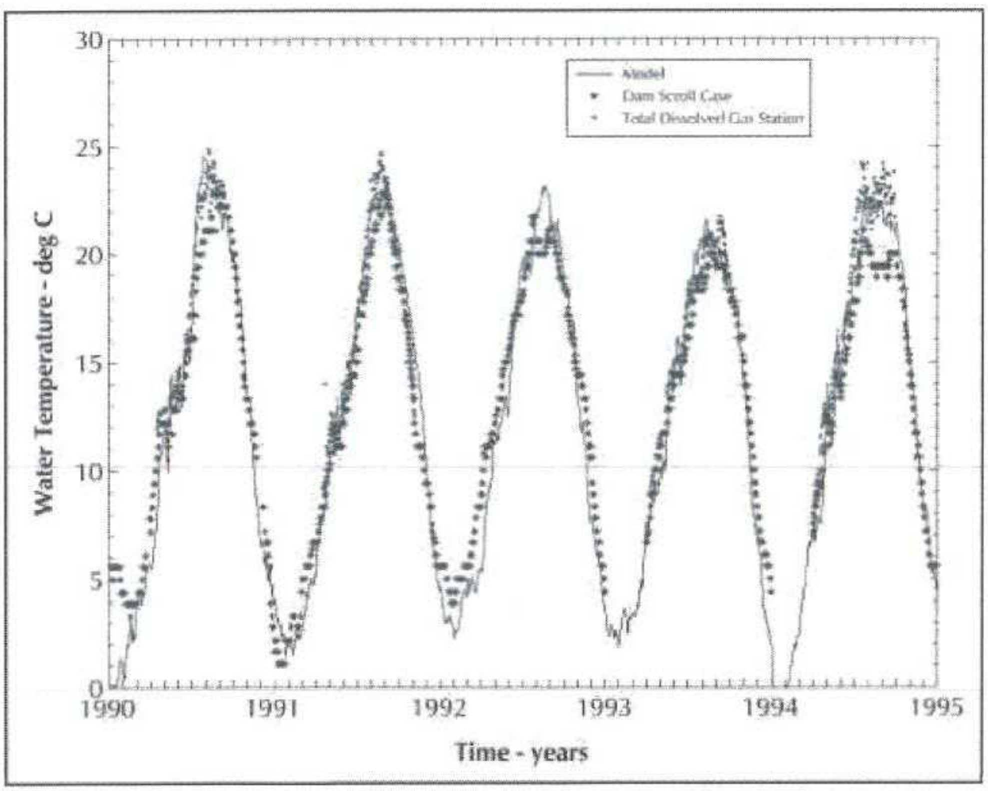

Figure 3. Comparison of predicted and observed water temperatures at Ice Harbor Dam on the Snake River for the period 1990-1994 (Yearsley, 2001).

Table 4
Comparison of Tribal and State Maximum Temperature Standards on the Columbia and Snake Rivers (EPA, 2001)

River Reach	Idaho	Oregon (7 day running avg. of the daily maximums)	Washington (Maximum)	Colville Reservation (Maximum)
Snake: Salmon R to OR Border	19 C daily avg. 22 C max	**Oct 1 to June 30 -** 12.8 C or natural **July 1 to Sep 30** 17.8 or natural		
Snake: Or Border to Clearwater R.	19 C daily avg. 22 C max		20 C or natural + .3 C	
Snake: Clearwater to mouth			20 C or natural + .3 C	
Columbia: Can Border to Grand Coulee			16 C or natural + .3 C	16 C or natural + .3 C*
Grand Coulee to Chief Joseph			18 C or natural + .3 C	16 C or natural + .3 C
Chief Joseph to Wells			18 C or natural + .3 C	18 C or natural + .3 C
Wells to Priest Rapids			18 C or natural + .3 C	
Priest Rapids to OR Border			20 C or natural + .3 C	
OR Border to mouth		20 C or natural	20 C or natural + .3 C	

* Applies from the Northern Boundary of the Colville Reservation (approximately River Mile 721) to Grand Coulee Dam

The model analyses showed that the most downstream location on the riverine portion of the Columbia River, Mile 4, was the critical location controlling the TMDL. In order to meet the standards at that location, all of the upstream reaches would have to have temperatures lower than the most stringent temperature standards in each reach.

Estimation of Natural Temperatures

Since there are no historical temperature data available before the dams were built, natural temperatures were estimated using RBM 10 by removing the dams and all human heat sources (point sources, etc.) from the model. The model was run with 30 years of meteorological data to simulate temperatures for the period 1970 to 1999 at each location in the rivers. At each site, the daily temperatures were averaged over the 30-year period to estimate the long-term average temperature for each day of the year. These values represent the **site potential** temperatures.

Comparison of these estimated natural temperatures with the current temperatures shows that the natural temperatures would fluctuate more widely due to both diurnal heating/cooling and day-to-day variations in the weather, and that the natural temperatures would cool much faster in the late summer and fall. These differences are illustrated in Figure 4 (for the Ice Harbor Dam on the Snake River).

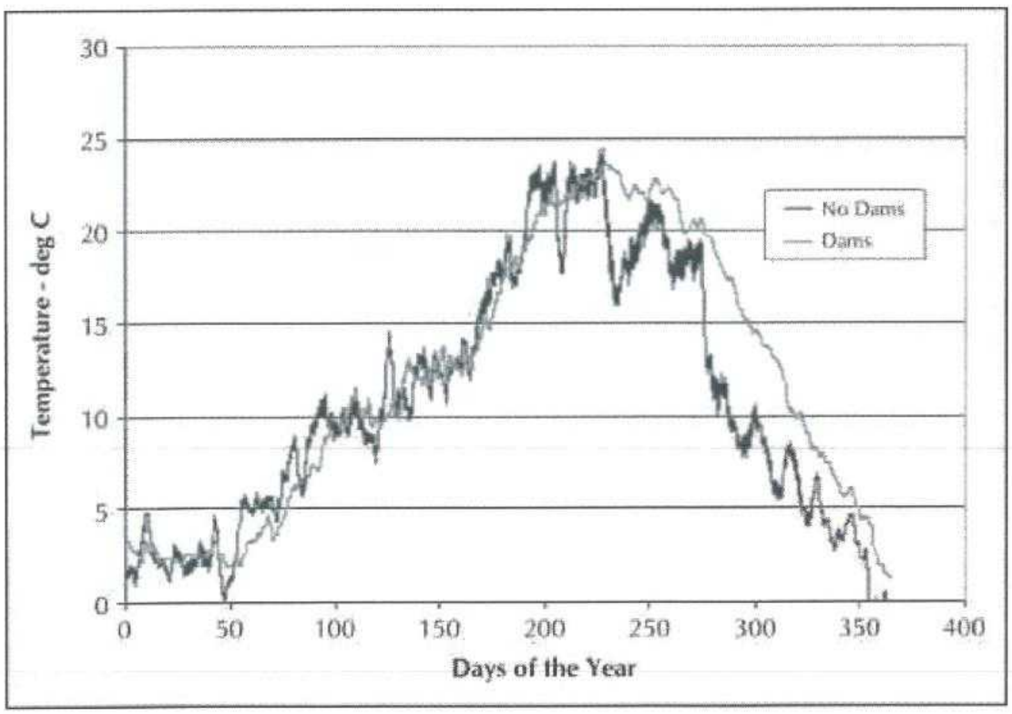

Figure 4. Comparison of predicted water temperatures at Ice Harbor Dam on the Snake River with the dams in place (current conditions) and with the dams removed (natural conditions) during 1990 (EPA, 2001).

The model analyses showed that temperature standards violations occurred in the natural free flowing rivers before the dams were built, but that the frequency of violations is higher with the current impounded temperature regime (EPA, 2001).

TRIBAL ALLOCATIONS OF HEAT, AND FUTURE GROWTH CONSIDERATIONS

Three major categories were considered in the heat load allocations for the TMDL:

- Point source discharges
- Dams
- Tributaries/nonpoint sources

Nonpoint sources such as irrigation return flows and heated runoff from the watersheds were assumed to be included in the tributary loads. All tributaries were allocated their existing heat loads since these loads were used in the modeling to define the natural (**site potential**) temperatures in the rivers. The impacts of the tributary loads on the Columbia/Snake main stem temperatures were small, except for the warming effects of the Snake River on the Columbia River, and the cooling effects of the Clearwater River on the Snake River.

Point source discharges were divided into two categories for the wasteload allocations:

- 11 large individual sources with discharges ranging from 200 to 511 MW
- 21 group allocations, which combined all of the smaller discharges along each of the 21 TMDL river reaches

The individual large sources were defined as facilities whose discharge raised the cross-sectional average river temperature by more than 0.014 deg. C at the discharge location. This temperature increase is 10 percent of the allowable increase over natural temperatures (0.14 deg. C) by the Oregon water quality standards (which are the most stringent standards for this component of the standards). The group allocations included 231 dischargers, of which 95 have individual NPDES permits, and the remaining 136 are covered by general permits. Discharges from the tribal lands are covered by general permits and are included in the group allocations.

The 11 individual large facilities and the 95 smaller facilities with NPDES permits were allocated the existing maximum loads specified in their discharge permits. The remaining point sources covered in the general permits are expected to have minimal effects on the river temperatures. The general permit sources were allocated 20 MW as a group for each of the 21 river reaches. This 20 MW allocation includes existing loads, as well as future growth. Tribal concerns were expressed at the September 6 meeting that the 20 MW growth allocations for the tribal reaches of the rivers may be too restrictive, particularly if certain types of commercial facilities were to be built in the future.

The load allocations for the dams was 0.01 deg. C over the **site potential** temperatures for all dams except Priest Rapids, which was given a 0.09 deg. C increase. The allocations for all sources were selected so that water quality standards could be achieved at Columbia River Mile 4 near the downstream end of the system, as well as at all of the upstream reaches. Although the existing point source discharges have a relatively small effect on the river temperatures, their existing heat loads leave very little reserve for additional heat loads from dams. The model analyses show that the dams are responsible for most of temperature increases in the Columbia and Snake Rivers associated with human influences.

ADEQUACY OF TEMPERATURE MONITORING STATIONS

A fairly extensive set of temperature monitoring data was available for the TMDL modeling. McKenzie and Laenen (1998) compiled and evaluated temperature data from 84 stations along the Columbia and Snake Rivers within the TMDL study area. This included data from all of the dams, several United States Geological Survey (USGS) monitoring stations on the rivers, and several other stations and monitoring programs. These data focused on the main stems of the two rivers. In addition, EPA compiled temperature data from the major tributaries that were included in the model from several sources, including Washington Department of Ecology (DOE), Oregon Department of Environmental Quality (DEQ), Idaho Power Company, and USGS.

As would be expected, the quality and accuracy of the data varies between monitoring sites. This is because of differences in the types, locations, and numbers of measurement instruments used, as well as differences in quality control for the instrumentation and data recording. EPA visited six dams on the Columbia, Snake, and Clearwater Rivers (McNary, Ice Harbor, Lower Monumental, Little Goose, Lower Granite, and Dworshak) to evaluate the monitoring stations (Cope, 2001). During the model calibration, an effort was made to use similar types of monitoring stations so that valid comparisons could be made between different sites along the rivers. During the data evaluation, it was apparent that the temperatures could be somewhat different between measurements in the fore bays, tail races, and dam scroll cases at the same dam location (EPA, 2001). In spite of certain data limitations, the existing temperature data were generally adequate for the one-dimensional TMDL modeling.

Monitoring to provide more detailed information for two-dimensional modeling has been improving over the last few years. For example, in Lake Roosevelt, the Bureau of Reclamation has installed thermistor strings in the fore bay from surface to bottom that take continuous measurements every 30 seconds. Tribal monitoring in Lake Roosevelt has also increased, with measurements extended deeper in the lake than earlier monitoring. Measurements are taken at 8 or 9 stations along the lake every few weeks. A meteorological station was added at the lake to get more accurate climatic data. EPA has also requested that the flow release data from Grand Coulee Dam be put in electronic form. Flow releases occur from several outlet locations (depths) at the dam, and since these releases have a major impact on the reservoir hydrodynamics, it is important to accurately characterize them for future two-dimensional modeling efforts. At the downstream reservoirs on the Columbia River, temperature is monitored continuously, but only at one depth about 15 feet below the dam, plus some downstream stations. On the Snake River, the Army Corps of Engineers and Bonneville Power Authority (BPA) are installing two to three strings of thermistors across the forebays of all dams. The Corps and BPA are acting separately to monitor the Snake River, but the efforts are compatible. The Corps has installed the forebay thermistor strings at the Snake River dams. BPA is funding Battelle to deploy strings upstream of Lower Granite Dam (within the impoundment and confluence of Snake and Clearwater Rivers) to support future two- and three-dimensional analysis in that area.

Assumptions for Columbia River Inflows from Canada

Since the upstream boundary for the TMDL analyses was the Washington-Canada border, water temperatures and flows on the Columbia River at the Canadian border were specified as input to RBM 10 based on monitoring data from this location. Daily monitoring data for the period 1970 to 1999 were used to drive the simulations at the upstream boundary of the model. The Canadian portion of the Columbia River has some very large impoundments that undoubtedly influence the temperature regime and flows in the U.S. portion of the river downstream. However, the Canadian waters are outside of U.S. jurisdiction, so measures to manage the Canadian flows and temperatures to improve conditions in U.S. waters cannot be included as part of the TMDL.

Perspective on Application to Pend Oreille River

The Pend Oreille River flows through Idaho and northeastern Washington into British Columbia and enters the Columbia River near the U.S.-Canadian border. The Pend Oreille River is one of many tributaries to the Columbia River. The TMDL analyses assumed that all heat loads from tributaries to the mainstem Columbia and Snake Rivers are the same as their existing and historical loading rates. These loads were based on stream flow and temperature monitoring conducted in the tributaries from the period 1970 to 1999 (or whatever years were available). The calculated loads from the monitoring data were used as input to the model. The use of existing loads was necessary since temperature TMDLs have not yet been established for almost all of the tributaries. Only one tributary to the Columbia/Snake River main stem, the Umatilla River, has already had a temperature TMDL established. However, the TMDL modeling showed that heat loads from most of the tributaries had only minor effects on the mainstem Columbia and Snake Rivers.

The TMDL model, RBM 10, was recently applied by EPA in a separate study to a portion of the Pend Oreille River to evaluate the effects of the Box Canyon Dam on the temperature in the river (Cope, 2002). The study area was the reach between Albeni Falls Dam and Box Canyon Dam (river miles 89 to 34). Although this reach has been 303(d) listed for being temperature impaired, the model study was performed in support of a Federal Energy Regulatory Commission (FERC) re-licensing of the Box Canyon Dam, rather than as part of a TMDL study. RBM 10 was used to assess how much the Box Canyon Dam increases water temperature in the river at the location of the dam compared to what the temperatures would be without the impoundment.

TMDL Implementation Plans

Implementation plans have not been formulated at the present time. EPA's responsibility is to determine the TMDL allocations necessary to satisfy water quality standards along all temperature impaired reaches of the Columbia and Snake Rivers. This TMDL does not address implementation issues. The implementation measures necessary to meet the allocations are left to the states and tribes. The TMDL is currently in the preliminary draft review stage. The states are working on some very general implementation recommendations that will be issued when the final TMDL goes out to the public.

Several temperature management measures will be considered to obtain cold water releases from the upstream reservoirs during the implementation. These may include alternate powerhouse/spill operations (e.g., altering use of Grand Coulee powerhouses to draw inflow from different elevations in the reservoir), installation of selective withdrawal structures, altered flood control management, and other measures that could provide cold water releases. These releases may have important effects on the thermal structure, water levels, flow rates, and current velocities in the impoundments, which could in turn have important environmental consequences. These issues will have to be addressed in later studies to be conducted during the implementation planning. It should also be noted that the TMDL is not the only planning effort that may affect future operation of the river system. For example, the Corps is currently evaluating a new flood control plan (VARQ) that could effect river management significantly.

There is a cold water release program from Dworshak Reservoir already in place that is releasing water into the Snake River. An evaluation of the impact of these and other planned releases will need to be considered during the implementation of the TMDL, which will require further monitoring and evaluation.

It is possible that additional cold water releases may be required from the Canadian reservoirs upstream of Lake Roosevelt, which would require international negotiations. Because of the substantive nature of the international issues, this would have to be considered a long range option.

Future Studies for Assessing Implementation Effects in Lake Roosevelt

Implementation of the load allocations in the TMDL will require temperature reductions in the reservoirs along the Columbia and Snake River main stems. This will require major cool water releases from the reservoirs located at the upstream boundaries of the study area. Lake Roosevelt, impounded by Grand Coulee Dam, is located at the upstream end of the U.S. portion of the Columbia River, and is the largest lake in the system. It is also the deepest lake, and has the largest temperature difference between the surface and bottom waters. However, the current temperature differences are much less than the historical temperature profiles because of the increased flow releases for power generation. For example, in the 1960's, the lake was much more stratified, had a well-developed thermocline, and had lower temperatures in the bottom waters. Currently, the bottom temperatures are warmer, and stratification is weaker and fluctuates spatially and temporally over the stratified season. Increasing the flow releases to attain the TMDL load allocations may further alter the thermal structure of the lake. In addition, these releases may cause significant changes in the lake surface elevation and in the current and flow regime through the lake, particularly near the outlets. These changes could have important consequences to the fisheries and other aquatic resources, as well as producing other environmental problems and disturbing cultural resources. The tribes have identified the following issues as areas of potential concern that should be evaluated during the implementation planning.

- Stratification effects
- Adequacy of cooling water supply
- Lake elevation changes
- Fish impacts– habitat degradation (temperature), entrainment, migration
- Cultural resources
- Toxic sediments
- Landslides
- Macrophytes

Although much of the focus is on the effects on Lake Roosevelt, some of these issues would also apply to some of the other reservoirs on tribal lands. Of particular concern was the ability of the TMDL model to evaluate these issues, and other potential modeling approaches that might be more appropriate.

The following discussion describes in general terms what types of implementation issues RBM 10 would be able to address, followed by a discussion of other modeling approaches that would be more suitable for addressing other issues that could not be evaluated with RBM 10. This is followed by more specific information on how the models could be used to evaluate each of the above potential problems.

APPLICATION OF RBM 10

EPA is using RBM 10 in the development of the TMDL to establish target temperatures at the Grand Coulee tailrace. RBM 10 could also be used during the implementation phase to assess effects of alternate Grand Coulee operations on downstream temperatures. This would be done by removing the portion of the model grid from Grand Coulee Dam to the Canadian border, and starting the simulations from the Grand Coulee tail race. The model could be run iteratively with different combinations of flow rates and temperatures to determine what combinations would meet the TMDL allocation requirements down stream. The temperature and flow release combinations would have to consider the existing temperature regime and storage volume in Lake Roosevelt. If the analyses showed that the required releases were small in comparison to existing releases for power generation, then the use of the existing temperature profiles would be a reasonable approximation until more detailed studies were conducted to evaluate temperature changes in Lake Roosevelt. If the required flow volumes were large, the corresponding temperatures could be selected to reflect a potential drop in the thermocline elevation as the lake surface elevation dropped, as well as potentially warmer bottom temperatures from decreased stratification.

The flow release estimates from the RBM 10 modeling could also be used to assess the potential drop in the Lake Roosevelt surface elevation. Knowing the required flow rates and their durations, the corresponding lake volume losses can be directly calculated. These volumes could then be compared with a graph of the lake storage volume at different surface elevations to determine the effects on the lake surface. This type of relationship is most likely already available, but if not, it could be easily developed from existing bathymetric information.

The flow release estimates from the RBM 10 modeling could also be used to estimate velocities in the vicinity of the outlets, and to assess potential fish entrainment problems.

TWO-DIMENSIONAL MODELING

Although RBM 10 can be used to estimate the flow releases that would be required to meet the TMDL allocations downstream of Lake Roosevelt, it is less useful for estimating temperature changes in Lake Roosevelt since large flow releases may be required and these flows could alter the existing thermal structure of the lake. The current flow releases for power generation and flood control have reduced thermal stratification relative to historical levels in the 1960's, so it is reasonable to expect that further changes may occur as a result of the TMDL implementation. Since Lake Roosevelt is long, deep, and narrow, a two-dimensional model with vertical layers and longitudinal segments would be an appropriate tool for evaluating these effects.

EPA has already initiated two-dimensional modeling of Lake Roosevelt (Yearsley, 2001) using the Army Corps of Engineers' CE-QUAL-W2 model (Cole and Buchak, 1995). This model is well developed, fairly widely used, publicly available, and supported by a public agency. It is an appropriate model to address the tribal concerns. EPA has also applied CE-QUAL-W2 to Lower Granite Dam on the Snake River (EPA, 2002b).

CE-QUAL-W2 (and other vertical two-dimensional models) divides the lake vertically into a series of layers and longitudinally along its length into a series of segments for the temperature calculations. The model assumes these segments and layers do not have significant temperature variations across their widths, and calculates averages over this lateral direction.

The model calculates heat exchange between the lake surface and the atmosphere similarly to RBM 10, but considers the distribution of heat from solar radiation to deeper layers from light penetrating the water column. Most importantly, density differences resulting from spatial differences in temperature are used to calculate stratification effects and the general circulation along the length of the reservoir. Stratification inhibits mixing of the surface and bottom waters, and influences the distribution of flows that result from inflows at the upstream end of the lake and outflows from Grand Coulee Dam. Because temperature in stratified lakes has a major influence on mixing and circulation, hydrodynamic calculations that determine water movements are an important part of two-dimensional lake models. This is an important difference from one-dimensional models, which assume temperature does not affect flows and allow the use of separate hydrodynamic models to provide flow, depth, and other channel geometry information.

The main processes driving the hydrodynamic calculations in two-dimensional models are the inflows, outflows, wind shear on the surface, and density differences due to spatial variations in temperature (and salinity in some systems). In addition to calculating heat exchange at the surface and flows through the lake, the model calculates the transport of heat between spatial segments due to both the flow of water between segments and mixing processes between adjacent segments (and layers). CE-QUAL-W2 adds or subtracts layers and upstream segments from the model grid to represent the effects of a rising or falling water surface. The vertical extent of the outlet withdrawal zone in the lake is calculated based on the flow rate, density gradient, and geometry of the outlet structure. The vertical location of inflowing tributaries in the model is calculated based on the temperature of the tributaries relative to the vertical temperature profile in the lake at the inflow location.

The types of data necessary for two-dimensional and one-dimensional modeling are similar. The major data types are:

- Bathymetric information (channel cross-sections at several locations along the length of the lake)
- Meteorological data (solar radiation, cloud cover, wind velocity, air temperature, relative humidity (wet bulb temperature), and atmospheric pressure). Solar radiation can be calculated in the model based on latitude, longitude, and time of day.
- Inflow rates and temperatures at the upstream end of the lake and for all important tributaries and point source discharges
- Outflow rates and locations for all outlet structures, and for any other significant outflow tributaries, water diversions, or other water withdrawals from the lake
- Temperature monitoring data to calibrate and verify the model

The major difference between the two-dimensional and one-dimensional model data requirements is that it is desirable to have more spatial resolution in the temperature monitoring data for two-dimensional modeling. The data requirements for three-dimensional modeling are also the same, except that more spatial resolution in the lateral direction across the width of the lake would be necessary.

The outputs from CE-QUAL-W2, or any other two-dimensional lake model, are the temperatures in each spatial segment, the velocities and flows between segments, and the fluctuations in water surface over the simulation period.

CE-QUAL-W2 also has a water balance routine that enables the user to make corrections to inflows/outflows discrepancies based on available elevation data (used as input). EPA is using this feature in their modeling of Grand Coulee and Lower Granite Reservoirs.

Because CE-QUAL-W2 is also a water quality model in addition to a temperature and hydrodynamic model, it can be used to assess other issues such as dissolved oxygen, nutrients, algal blooms, and bacteria. Additional monitoring data for the constituents of concern, both in the lake and in the upstream inflows, tributaries, and significant point sources, would be necessary for these types of analyses.

The following sections provide additional information on how the modeling could be used to address each of the major implementation issues identified by the tribes. This information can be used to develop future study plans to evaluate these issues.

STRATIFICATION EFFECTS

The existing flow releases from Lake Roosevelt for power generation and flood control have altered the thermal structure of the lake, resulting in less stratification and warmer bottom temperatures than historical conditions in the 1960's when the flows were lower. The operational changes in Lake Roosevelt necessary to meet the TMDL would be based on a number of different things including the amounts, timing, and where in the lake water is withdrawn for flood control, the powerhouses, and irrigation, as well as changes in lake levels during different times of the year. The future operations would change the temperature profile released from the dam throughout the year. This could in turn affect the patterns of stratification in the lake, possibly making portions of the lake warmer during some times of the year and cooler during other times. These changes may have important consequences on the fish habitat.

A two-dimensional lake model is ideal for assessing these effects, since it predicts the vertical temperature distribution near the dam as well as at various locations along the length of the reservoir.

Three-dimensional models could be used to calculate the additional temperature variations across the width of the lake, but these are not expected to be significant due to the long, narrow shape of the lake. Three-dimensional models are also much more difficult and expensive to set up and run, and should have more temperature monitoring stations than a two-dimensional model.

At the other extreme, a one-dimensional lake model that divides the lake into vertical layers and assumes the vertical temperature distribution is relatively uniform horizontally along the length of the lake could be used for more simplified analyses of stratification. However, the long length of Lake Roosevelt combined with the fact that it is a run-of-the-river reservoir with fairly high flow rates makes a two-dimensional model the most appropriate choice.

The lake model could be run with different release scenarios to determine which combination of flow rates and release depths had the least negative impacts on lake stratification and still met the downstream TMDL allocation requirements. This would most likely involve iterative runs with the two-dimensional model and RBM 10. Two-dimensional models could also be set up for more detailed stratification analyses of other reservoirs in the Columbia and Snake River main stems, particularly the deeper ones that are currently stratified.

Adequacy of Cooling Water Supply

Fairly large flow releases may be required from Lake Roosevelt to meet the TMDL allocations downstream. Since these releases may adversely affect temperatures in the lake and since the releases will probably involve fairly large volumes of water, an obvious question is whether the lake will have enough cool water available to satisfy the downstream heat allocations. Again, a two-dimensional model is the appropriate tool to answer this question since it will calculate both the changes in volume and the changes in temperature that will occur as water is released from the lake. The model could be run initially to determine if this is a significant issue, and if it was, the model could be run with different release scenarios to determine a release plan that would not deplete the cool water supply in the lake. Again, iterative runs with RBM 10 may also be required to determine if the downstream allocations would be met.

Lake Elevation Changes

The anticipated flow releases necessary to satisfy the downstream TMDLs may result in significant elevation changes for the surface of Lake Roosevelt. The lake surface already fluctuates seasonally due to the releases for flood control and power generation. For example, in 1998 the surface elevation fluctuated about 35 feet (Yearsley, 2001). The surface fluctuations could increase and their timing could change as a result of the releases required for the TMDLs.

Lake elevation changes can be evaluated fairly easily and do not require the use of models. The bathymetric information can be used to construct a graph of lake storage volume versus surface elevation. This type of relationship is standard information and most likely already exists for Lake Roosevelt. Once the flow release estimates are known, it is simple to estimate the surface elevation fluctuations by performing a water budget based on mass balance calculations. The inflow and release rates (along with precipitation and evaporation estimates) can be used to calculate the lake volume changes, and the volume changes can be used in conjunction with the reservoir stage-volume relationship to determine the changes in surface elevation.

However, since a two-dimensional lake model would most likely be used to assess stratification effects, adequacy of cooling water supply, and other issues in the lake, surface elevation changes can be directly obtained from the model output since elevation is one of the basic outputs from the model. CE-QUAL-W2 changes the thickness of the top layer to accommodate surface fluctuations and adds or subtracts layers and upstream segments to the model grid as the calculated water surface rises and falls.

Fish Impacts

Several important fishery impacts could potentially occur as a result of the TMDL flow releases and the corresponding changes in Lake Roosevelt and the other impoundments along the Columbia and Snake Rivers. These include habitat degradation, increased fish entrainment through the outlet structures, and migration impacts.

Habitat degradation could occur in Lake Roosevelt due to changes in the temperature structure and the reduction or elimination of cool waters in the lower portion of the lake, or through the destruction of littoral habitat through major water level fluctuations. Both of these issues could be evaluated using the results of the two-dimensional modeling described above, since the spatial distribution of temperate and water surface elevations are basic outputs from the model.

Fish entrainment through the outlet structures depends on the outlet flow rates, velocities in the vicinity of the outlet, and fish distribution in the lake. The two-dimensional lake model and RBM 10 would be used to determine the outlet flow rates and the release schedule necessary to meet the TMDLs. Velocities near the outlet structure could then be calculated from the flow rates and information on the outlet structure geometry and the temperature distribution near the outlet. Although the two-dimensional model calculates velocities, these velocities represent average velocities across the width of the lake, rather than the local velocity near the intake. The temperature distribution calculated by the model could be used to help estimate the distribution of fish near the outlet based on their temperature preferences. The above information could be used in conjunction with existing data on fish entrainment to estimate the increases associated with the TMDL flow releases.

Fish migration could be influenced by changes in the temperatures and velocities along the Columbia and Snake Rivers. The TMDL should improve temperature conditions along the rivers. RBM 10 and the two-dimensional model of Lake Roosevelt will provide the information necessary to estimate temperatures, flows, and velocities throughout the system. However, local changes in structures such as fish ladders may require additional assessment.

Cultural Resources

Major draw down of the water surface in Lake Roosevelt to provide the flows necessary for the TMDL may expose cultural resources that are currently inundated. These impacts can be assessed using the water surface elevations calculated from the modeling or the water budget mass balance, along with a bathymetric map of the lake and information on the locations of the cultural sites.

Toxic Sediments

Increased fluctuations in the water surface of Lake Roosevelt associated with the TMDL releases could expose toxic sediments that are currently buried in the lake. The results of the modeling or water budget calculations could be used to determine the extent of the surface fluctuations, which could in turn be used with lake bathymetric information to determine the sediment areas that would be exposed. This information could be used to design sediment monitoring programs. Human and ecological risk assessments could be conducted with the monitoring results to evaluate the effects of potential toxic sediment exposure.

Landslides

Landslides can occur around the perimeter of Lake Roosevelt when the lake is at full pool, and when rapid drops occur in the water surface elevation. Information on the timing and extent of the water surface fluctuations is necessary to perform a geotechnical analysis of the landslide potential from the changes in Lake Roosevelt associated with the TMDL releases. The results from the two-dimensional modeling or the water budget calculations would provide this information.

Macrophytes

Macrophyte growth depends on light availability, so depending on the turbidity levels in the lake, macrophytes can grow to depths where the light extends to near the bottom. Because Lake Roosevelt is fairly deep, macrophyte growth is restricted to the shallower nearshore areas. As the water surface drops, the potential macrophyte habitat extends further into the lake. However, if the drops occur for extended time periods, the macrophytes in the exposed areas above the waterline may become desiccated and die. Analysis of the potential effects on macrophytes requires information on the extent and timing of the water surface fluctuations along with bathymetric data and lake turbidity data. The two-dimensional modeling or water budget calculations would provide the surface fluctuation information.

References

Bonneville Power Administration et al. 1994. Columbia River System Operation Review. Appendix M, Water quality. DOE/EIS-0170. Bonneville Power Administration, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation, Portland, Oregon.

Cole, T.M. and E.M. Buchak. 1995. A Two-dimensional Laterally Averaged, Hydrodynamic and Water Quality Model. Version 2.0. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Cope, B. 2002. Assessment of the Impact of Box Canyon Dam on the Temperature of the Pond Oreille River. US Environmental Protection Agency, Seattle, WA.

Cope, B. 2001. EPA Memo. Site Visits to Six Dams on the Columbia and Snake River.

Environmental Protection Agency. 2001. Problem Assessment for the Columbia/Snake River Temperature TMDL, Preliminary Draft, October 18, 2001. US Environmental Protection Agency, Seattle, WA.

Environmental Protection Agency. 2002. Columbia/Snake Rivers Temperature TMDL, Preliminary Draft, September 3, 2002. US Environmental Protection Agency, Seattle, WA.

Environmental Protection Agency. 2002b. Temperature Simulation of the Snake River Above Lower Granite Dam Using Transect Measurements and the CE-QUAL-W2 Model, EPA 910-R-02-008, September 2002.

Leopold, L.B. and T. Maddock. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252. U.S. Geological Survey.

McKenzie, S.W., and A. Laenen. 1998. Assembly and Data-quality Review of Available Continuous Water Temperatures for the Main Stems of the Lower- and Mid-Columbia and Llower-Snake Rivers and Mouths of Major Contributing Tributaries. NPPC Contract C98-002. Northwest Power Planning Council, Portland, Oregon.

Normandeau Associates. 1999. Lower Snake River Temperature and Biological Productivity Modeling. R-16031.007. Preliminary review draft. Prepared for the Department of the Army, Corps of Engineers, Walla Walla, Washington.

U.S. Army Corps of Engineers, Walla Walla District. 2002. Final Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement.

Wunderlich, W.O. and R. Gras. 1967. Heat and Mass Transfer Between a Water Surface and the Atmosphere. Tennessee Valley Authority, Division of Water Cont. Planning, Norris, Tennessee.

Yearsley, J.R. 1969. A mathematical model for predicting temperatures in rivers and river-run reservoirs. Working Paper No. 65, Federal Water Pollution Control Agency, Portland, Oregon.

Yearsley, J. R. 2001. Application of a 1-D Heat Budget Model to the Columbia River System. US Environmental Protection Agency, Seattle, WA.